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THE RELATIONSHIP BETWEEN THE MAXIMUM FORCE EXERTABLE BY THE HAND IN A HORIZONTAL PULL AND THE ENDURANCE OF A SUB-MAXIMAL HOLDING RESPONSE

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The Relationship Between Strength and Duration of Muscular Responses
Task 09
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ABSTRACT

THE RELATIONSHIP BETWEEN THE MAXIMUM FORCE EXERTABLE BY THE HAND IN A HORIZONTAL PULL AND THE ENDURANCE OF A SUB-MAXIMAL HOLDING RESPONSE

OBJECT

To determine the relationship between measures of maximum strength of horizontal pull by the hand and the endurance of a sub-maximal holding response at a variety of body positions.

RESULTS AND CONCLUSIONS

A corrected correlation of .88 was obtained between the measures of peak force and the duration of the holding response. It may be assumed that any change in the working-situation which produces an increase in the peak force which can be applied to a control will reduce the effort required for maintaining a given output, and the duration of the holding response will be increased.

One may use the principles concerning the effects of body position and control placement derived from the measurement of peak force and apply them to those situations in which sub-maximal forces must be maintained for longer periods of time. Since the measure of peak force is more reliable and more easily obtained than the measure of duration, the results of this study encourage the continuation of the practice of assessing the effects of anatomical variables on working efficiency by measuring peak force.

RECOMMENDATIONS

Whether a person is required to apply a large force to a control for a short period of time by pulling horizontally, or whether a lesser force must be maintained for longer periods of time, performance will be best when the leg and arm are almost straight and the thigh is elevated above the horizontal.

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THE RELATIONSHIP BETWEEN THE MAXIMUM FORCE EXERTABLE BY THE HAND IN A HORIZONTAL PULL AND THE ENDURANCE OF A SUB-MAXIMAL HOLDING RESPONSE

I. INTRODUCTION

Most studies of the effect of limb position and body-support characteristics on the force which can be applied to a control have been concerned primarily with the maximum momentary output. That is, the subject was instructed to try to attain his maximum output within a period of only a few seconds, and only the peak force was measured. Typical of these studies are those by Hunsicker (6) and Caldwell (1, 2), who employed trial durations of 5 to 8 seconds. The question arises as to whether the recommendations concerning control placement, etc., derived from such studies can be applied to those work-situations in which an operator must maintain somewhat less than his maximum possible output for comparatively long periods of time. It has been assumed that the control position, or body attitude, at which a person can develop the greatest control force is also that at which a given sub-maximal force can be maintained for the longest period of time. However, this relationship has not been demonstrated in work-situations similar to those used by Hunsicker and Caldwell.

Elbel (5) reported that the less the pressure that had to be exerted on a foot pedal, the longer the pressure could be maintained. That is, he found an increase in the duration of the 'holding response" as the required output was reduced. Darcus (4) found that the time a supinating torque could be applied to a handle decreased progressively as the torque to be maintained was increased. He reported, too, that the endurance of the holding response decreased as the hand was rotated into the position in which the momentary strength of the response was weakest; that is, toward full supination.

If the expected relationship between peak-force and endurance of a sub-maximal holding response is obtained in the present study it would then be possible to make recommendations about control placement and body stabilization in a variety of work-situations from the data supplied by Hunsicker and by Caldwell.

II. EXPERIMENTAL

A. Apparatus

The apparatus employed in this study consisted of an adjustable isometric dynamometer handle, a display for use by the subject, an

adjustable seat assembly and foot-rest, and a strain amplifier and recorder. The apparatus exclusive of the amplifier and recorder is shown in Figure 1. The handle was mounted on a ball which was secured to a steel bar on which strain-gauges were mounted. The four gauges, which were wired as a Wheatstone Bridge, fed into the input of a strain amplifier. As the subject exerted a force against the handle, two of the gauges were lengthened and those on the opposite side of the bar were shortened. When the bridge circuit was thrown out of balance, a current proportional to the change in resistance of the gauges was fed into the amplifier. This was then amplified and fed into an ink-writing oscillograph. The dynamometer handle was calibrated against known weights so that the pen deflections could be converted into pounds of force. The handle was adjustable to produce a broad range of elbow-angles.

The subject display was a voltmeter with a scale marked in pounds connected in parallel with the oscillograph. A one-stage amplifier in parallel with the display energized a polar relay to which red and green lights were connected. These display lights were used only during the measurement of the holding response. By means of a bias control, the amplifier could be set to turn on a red light if the output fell below a given value and a green light when the output exceeded this value. Thus it was possible to set a goal output for a subject and simply instruct him to keep the green light on as long as possible. When his output fell below this goal, the red light came on, and he knew immediately that more force had to be applied to the handle. This supplementary display was necessary because a subject under heavy physical strain apparently has difficulty in attending to the needle of the voltmeter. Also as a subject nears the limit of his endurance gross body tremors develop which set the needle into oscillation. This makes it difficult to tell when the output drops below the goal value. The action of the lights, however, was unequivocal. Whenever the green light was on, a small DC voltage was applied to the second channel of the recorded which produced a "step" in the record. Measurement of the duration of the step provided a record of time the subject exceeded the goal output value.

The seat had vertical, lateral, and fore-and-aft adjustments which made it possible to place all subjects, regardless of size, in the same position with respect to the handle. When the seat was properly adjusted the center of the glenohumeral joint was at the height of the center of the handle. The line connecting the center of the handle and the glenohumeral joint was at right angles to the lateral plane of the

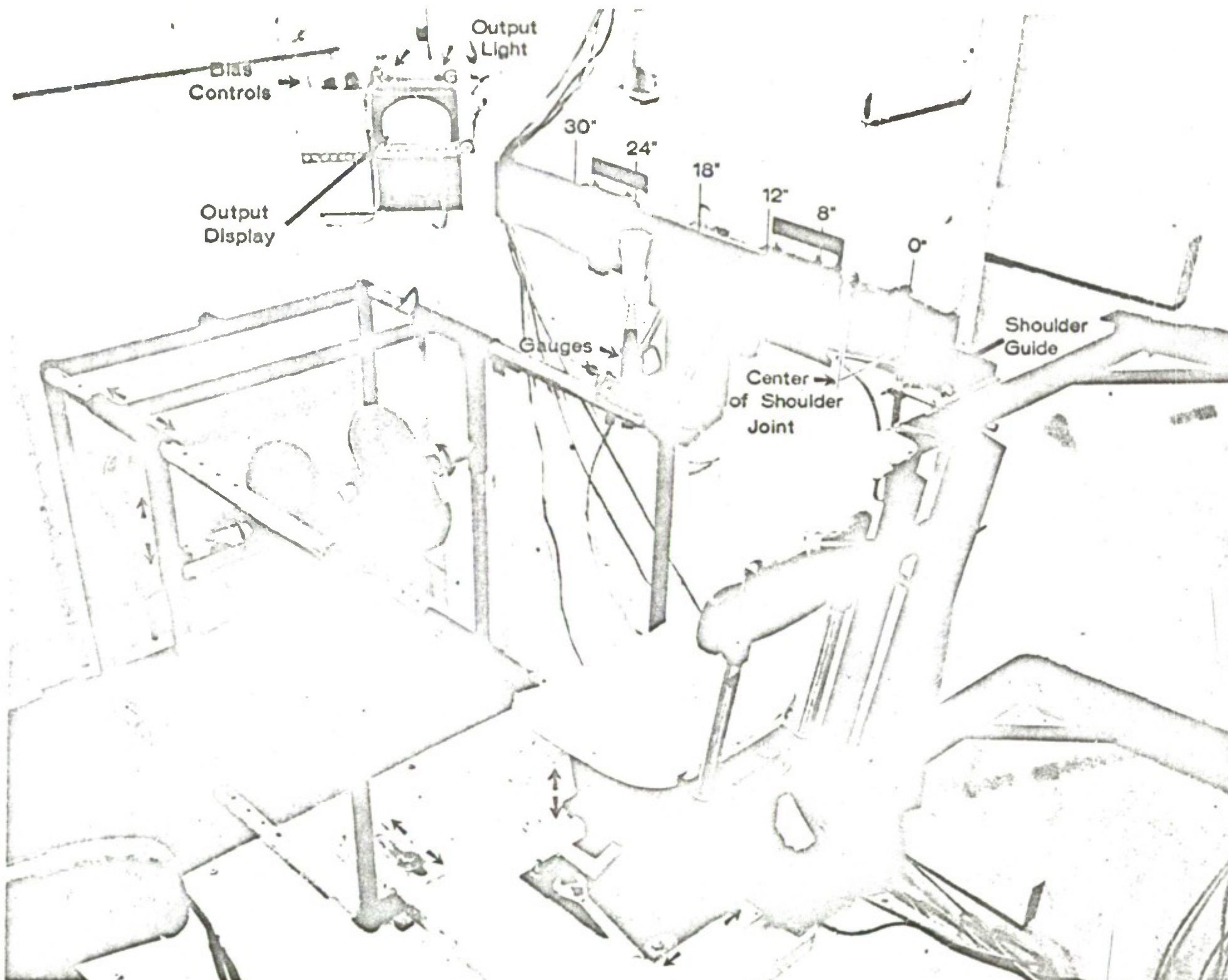

Fig. 1. Apparatus

body. Also the seat was adjusted fore-and-aft to align the shoulder joint with the zero point of the scale along which the handle was adjusted.

The dynamometer handle was adjustable along its support to produce elbow-angles ranging from about 40° to 180°, or from near maximum flexion to maximum extension.

The foot-rests were 6" x 12" steel plates covered with hard, corrugated rubber. The distance between the centers of the plates was 12 inches. The plates were free to pivot on a horizontal shaft so that the subject could select a foot-rest angle at which the plates would not pivot when pressure was applied to them. The foot-rest distance could be varied from approximately 21 to 40 inches from the hip-joint and from 2 inches above the seat to 16 inches below the seat. These foot-rest adjustments permitted the selection of the various leg positions used in the study.

B. Subjects

The ten subjects used in this study were technical and professional laboratory personnel of USAMRL. These were obtained solely on the basis of availability without regard to size or body type. The subjects reported no physical injuries or abnormalities which would be likely to interfere with the performance of the task. The weights of the subjects ranged from 141 to 195 pounds with a mean of 171 pounds. Their heights ranged from 66 inches to 74 inches with a mean of 68.9 inches. The age range was from 22 to 39 years.

C. Procedure

During the week prior to the actual testing the subjects were measured to determine the handle and foot-rest positions required to produce the necessary elbow-, thigh-, and knee-angles. Also the proper seat position was determined for each subject. The seat adjustments were recorded and used on all subsequent days of testing. The seat-back, a curved, foam-rubber covered piece of steel 12 inches wide and 4 inches high, was placed 14 inches above the level of the seat.

Prior to the experiment proper the subjects were given practice in developing a maximum momentary force, and in maintaining a goal output as long as possible. These two trials were always presented as a pair in one session. Five such sessions were presented for practice.

The peak force was determined first. Then after a short rest the endurance of the holding response was measured. All practice was given in one of the conditions used in the study. The handle was set to produce an elbow-angle of 95°, and the foot-rest was positioned to produce a thigh-angle of 0° and a knee-angle of 110°. (When the thigh-angle was at 0° the shaft of the thigh was parallel to the floor. A thigh-angle of 20° means that the long axis of the thigh was 20° above the horizontal. The knee-angle refers to the angle between the long axes of the thigh and lower leg.) This particular position was used during practice because previous peak force data had shown this to be the poorest of the 20 positions. One object of the five practice trials was to obtain a goal output for each subject sufficiently low that it could be attained at all positions, and yet high enough that it would provide a challenge even at the most favorable position. The pairs of trials were given at least 4 hours apart. On the first trial the subject was instructed to pull as hard as he could and to continue trying to reach a higher output until the trial was terminated by the experimenter at the end of 8 seconds. He was told to apply force gradually to the handle so as to combat the tendency to "slam" the control, and thus produce an artificially high output of short duration. The peak output was generally reached within 2 or 3 seconds. The peak output was noted, and 80% of this value was selected as the goal for the subsequent endurance trial. The amplifier gain of the display was set so that if the subject's output fell below this goal the red light would come on, and he would know to increase his output. After a rest of 3 minutes the second trial was given in which the endurance of the holding response was measured. The subject was told the output which he should maintain and that his task was to keep the green light on as long as possible. The trial was terminated when the subject ceased responding, or when he was unable to turn the green light on again within 3 seconds. The mean peak-output for the five practice trials for each subject was used as his goal for all subsequent endurance trials. This procedure insured that the goal set for each subject was proportional to his peak force.

In the experiment proper each subject was tested under 20 different conditions. Five elbow-angles (95°, 110°, 125°, 140°, and 155°) were combined with two thigh-angles (0° and 20°) and two knee-angles (110° and 150°) to produce the 20 conditions. The various arm and leg positions are shown in Figure 2, page 6. Each subject received a different random order of presentation of the conditions. Two sessions were given each day with approximately 4 hours between sessions. In each session the subject was given 2 trials. The timing of the trials and the procedure were exactly the same as those employed during the practice period.

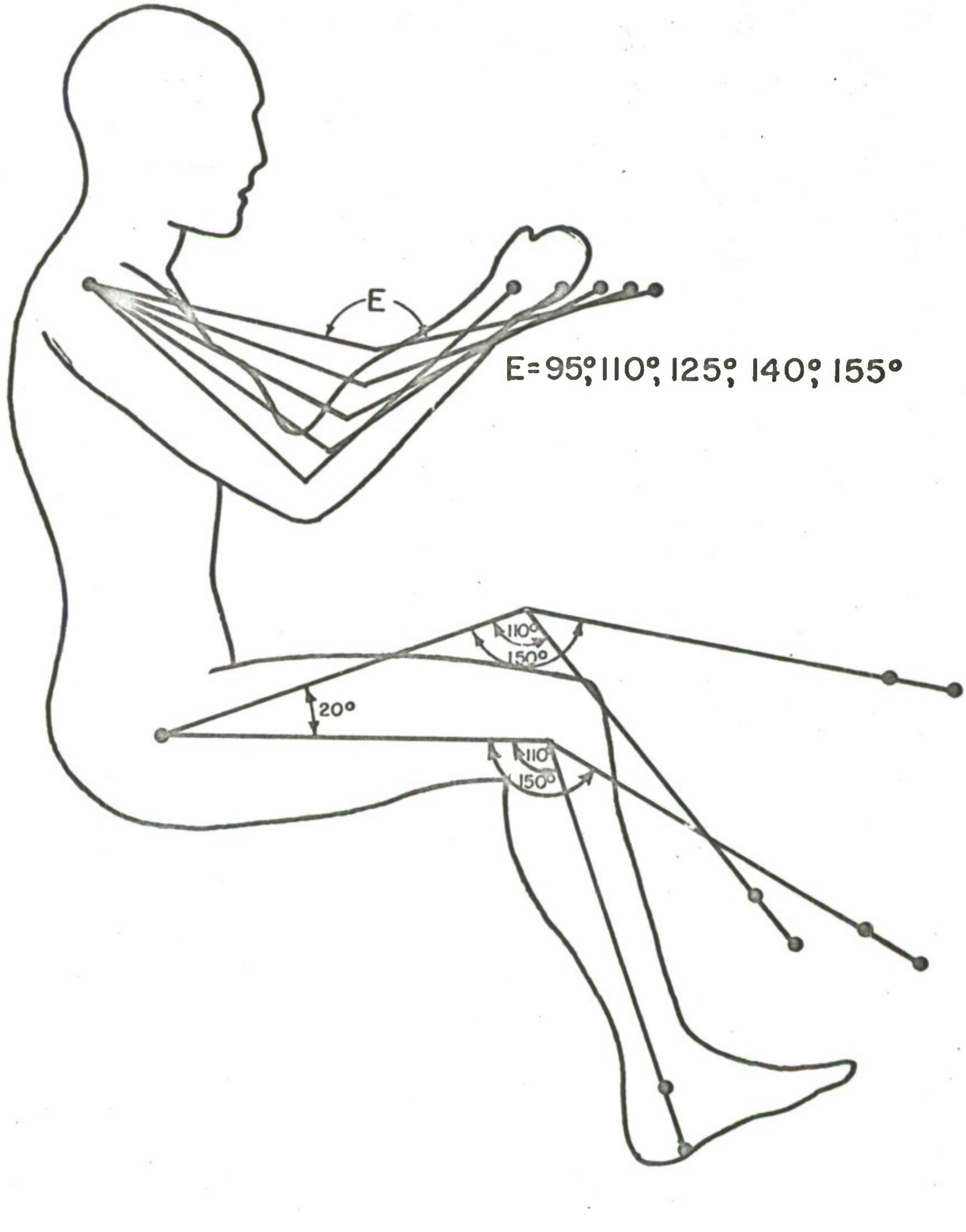

Fig. 2 Diagram showing the various arm and leg positions.

III. RESULTS AND DISCUSSION

A. Peak-Force

The peak-output data are presented in Table 1 and the analysis of variance of these data is shown in Table 2. This portion of the study is essentially a replication of a previously reported study (3). It may be seen from Table 1 that as the thigh-angle was increased from 0° to 20° there was an increase in mean force from 113.2 pounds to 127.6

TABLE 1

MAXIMUM STRENGTH IN POUNDS OF HAND PULL

	Thigh-Angle 0°			Thigh-Angle 20°			
Elbow-Angle	Knee-Angle 110°	Knee-Angle 150°	Mean	Knee-Angle 110°	Knee-Angle 150°	Mean	Mean
95°	94.8	114.3	104.6	112.6	122.9	117.8	111.2
110°	97.9	123.0	110.4	120.7	126.1	123.4	116.9
125°	100.4	123.7	112.1	122.1	132.7	127.4	119.7
140°	100.3	132.0	116.2	129.1	138.9	134.0	125.1
155°	104.6	141.0	122.8	129.2	142.0	135.6	129.2
Mean	99.6	126.8	113.2	122.7	132.5	127.6	120.4

Mean 110° = 111.2; Mean 150° = 129.6

TABLE 2

ANALYSIS OF VARIANCE OF DATA FOR THE MAXIMUM FORCE OF HAND PULL

	Source of Variance	df	MS	F	Error Term
1	Thigh-Angles (T)	1	10,411.3	27.65**	7
2	Knee-Angles (K)	1	17,094.1	43.98**	9
3	Elbow-Angles (E)	4	1,973.9	22.72**	PE_2
4	Subjects (S)	9	9,764.8	25.12**	9
5	T x K	1	3,793.0	41.45**	PE_1
6	T x E	4	47.2	..	PE_1
7	T x S	9	376.6	4.12**	PE_1
8	K x E	4	170.4	1.86	PE_1
9	K x S	9	388.7	4.25**	PE_1
10	E x S	36	108.1	1.18	PE_1
11	T x K x E	4	95.9	..	15
12	T x K x S	9	229.8	1.74	15
13	K x E x S	36	36.6	..	15
14	T x E x S	36	70.9	..	15
15	T x K x E x S	36	131.9		
Total		199			

**Significant at 1% level of confidence.

PE_1 = 11, 12, 13, 14, 15 = 91.50

PE_2 = 10, 13, 14, 15 = 86.89

pounds. Though this represents an increase in output of only 13%, the F-ratio for "Thigh-Angles" was significant at less than the 1% level of confidence. The significant "Thigh-Angles X Subjects" interaction indicates that there were individual differences in the magnitude of this effect.

A statistically significant interaction was obtained between "Thigh-Angles" and "Knee-Angles". In Table 1 it is evident that the effect of the knee-angle on the force of the response was different at the two thigh positions, though the 150° knee-angle was superior in both cases. When the thigh was horizontal (0°) there was a difference of 27.2 pounds between the outputs at the two knee positions, but when the thigh-angle was increased to 20° the difference between the two means dropped to 9.8 pounds.

The F-ratio for "Knee-Angles" was significant at less than the 1% level of confidence. The mean output was 111.2 pounds at the 110° knee-angle and 129.6 pounds at the 150° angle. Thus, as the knee-angle was increased from 110° to 150° there was an increase in strength of approximately 17%. Though this effect was small, every subject showed an increased output with an increase in knee-angle. The significant "Knee-Angle X Subjects" interaction demonstrates that there were individual differences, however, in the magnitude of this effect.

The effect of the thigh- and knee-angles on peak force reflect the importance of body stabilization in the production of control forces. The knee-angle influences the force exertable by the legs against the back-rest by varying the output of the toggle formed by the legs between the foot- and back-rests. (That the leg does operate as a toggle is supported by evidence from a prior study (3).) The effectiveness of this force in stabilizing the body is determined by its angle of application to the back-rest. If the thigh-angle is less than 0°, the force exerted against the back-rest tends to displace the subject upwards in his seat, and he is poorly stabilized. On the other hand, if the thigh-angle is greater than 0°, this force tends to wedge the subject into his seat, and he is firmly supported. It is obvious that the force applicable to a control is in many cases limited by the body's ability to withstand the counter-force, and this is determined by the degree of stabilization of the body.

The F-ratio for "Elbow-Angles" had a probability value of less than 1%. The mean force increased from 111.2 pounds at the 95° angle to 129.2 pounds at 155°. This represents an increase in output of 16%.

In every major respect these results are identical with those obtained previously--an increase in output as body stabilization was

improved by either increasing the elevation of the thigh or by straightening the leg, and an increase in output as the arm was straightened.

B. Duration of the Sub-maximal Response

The duration data are presented in Table 3, and the analysis of variance is shown in Table 4. The F-ratio for "Thigh-Angles" was significant at less than the 1% level of confidence. The mean duration

TABLE 3

DURATION IN SECONDS OF THE HOLDING RESPONSE (PULL)

	Thigh-Angle						
	0°			20°			
Elbow-Angle	Knee-Angle 110°	150°	Mean	Knee-Angle 110°	150°	Mean	Mean
95°	23.3	22.8	23.1	23.9	27.4	25.6	24.4
110°	23.5	31.9	27.7	28.8	25.9	27.4	27.5
125°	29.7	31.8	30.8	34.2	35.9	35.1	32.9
140°	27.9	37.2	32.6	42.2	36.8	39.5	36.0
155°	31.3	41.6	36.4	44.3	44.3	44.3	40.4
Mean	27.1	33.1	30.1	34.7	34.1	34.4	32.2

Mean 110° = 30.9; Mean 150° = 33.6

TABLE 4

ANALYSIS OF VARIANCE OF DATA FOR THE DURATION OF THE HOLDING RESPONSE (PULL)

	Source of Variance	df	MS	F	Error Term
1	Thigh-Angles (T)	1	911.20	11.64**	PE_2
2	Knee-Angles (K)	1	348.72	4.45*	PE_2
3	Elbow-Angles (E)	4	1662.89	21.24**	PE_2
4	Subjects (S)	9	1492.57	18.78**	PE_3
5	T x K	1	534.98	6.86**	PE_1
6	T x E	4	110.79	1.42	PE_1
7	T x S	9	135.31	1.73	PE_1
8	K x E	4	21.48	..	PE_1
9	K x S	9	61.54	..	PE_1
10	E x S	36	69.26	..	PE_1
11	T x K x E	4	156.93	1.21	15
12	T x K x S	9	69.66	..	15
13	K x E x S	36	38.26	..	15
14	T x E x S	36	70.38	..	15
15	T x K x E x S	36	127.23		
Total		199			

*Significant at 5% level of confidence. **Significant at 1% level of confidence.

PE_1 = 15, 14, 13, 12 = 77.93 PE_2 = 15, 14 13, 12, 10, 9, 7 = 78.26

PE_3 = 15, 14, 13, 12, 11, 10, 9, 8, 7, 6 = 79.45

of the holding response increased from 30.1 seconds at the 0° thigh-angle to 34.4 seconds at the 20° position. This represents an increase in duration of about 14%. It should be noted in Table 4 that a significant interaction was obtained between "Thigh-Angles" and "Knee-Angles." An examination of Table 3 reveals that when the knee-angle was 110° an increase in thigh-angle of 20° resulted in an increase in duration of 7.6 seconds while at the greater knee-angle this change in thigh-position resulted in an increase of only 1 second.

The duration of the holding response increased from 30.9 seconds at the 110° knee-angle to 33.6 seconds at the 150° knee-angle. Thus, there was an increase in duration of 8% as the knee-angle was increased from 110° to 150°. This effect was significant at the 5% level of confidence.

The F-ratio for "Elbow-Angles" was significant at less than the 1% level of confidence. The elbow-angles had a much greater effect on the duration of the response than did either the thigh- or knee-angles. The mean duration increased from 24.4 seconds at the 95° elbow-angle to 40.4 seconds at the 155° angle. Thus, there was a 66% increase in duration from the poorest to the best elbow position, whereas for the thigh and knee positions this difference amounted to 14% and 8%, respectively.

C. The Relationship Between Peak Force and the Duration of the Holding Response

A comparison of the peak-force and duration data reveals that the three anatomical variables have essentially the same effects on the two measures. Thus, it may be said that the arm and leg positions most favorable for the production of short-term responses are also the ones most favorable for the maintenance of a submaximal output. The correlation between the peak-output and duration scores for the 20 experimental conditions was computed. These product-moment correlations for the 10 subjects were as follows: .36, .40, .48, .61, .66, .70, .71, .73, .80, and .88. The first two correlations did not attain statistical significance, the *r* of .48 was significant at the 5% level of confidence, and the remaining 7 were significant at less than the 1% level of confidence. The correlation between the two sets of means was .76, $p < .01$.

The reliability of the peak force and duration measures were obtained on an independent sample of 14 subjects who were measured twice with the elbow-angle at 95°, the thigh at 0°, and the knee at 110°. The conditions of measurement were the same as those used in the

present study. The second measurements were made from 2 to 5 days after the first. The test-retest correlation for peak force was .93, and for duration it was .81. When the correlation of .76 obtained between the measures of peak and duration in the present study was corrected for the attenuation due to the relative unreliability of the two measures a corrected $\underline{r}$ of .88 was obtained.

It has been demonstrated that those anatomical characteristics most favorable for the production of muscular forces of short duration are also most favorable for the maintenance of sub-maximal forces. Thus, it would seem that when a subject must maintain a certain output any change in the situation which would produce an increase in his maximum output would reduce his effort level, and the time for which he could maintain the response also would be extended. It has been shown that as the elbow-, knee-, or thigh-angle increases there is an increase in the force which can be applied to the dynamometer. Thus, as these three angles are increased less effort should be required to produce and maintain a given output, and fatigue should develop at a slower rate.

The endurance of a holding response is more dependent upon the "relative load" placed on the body than upon the absolute load. The relative load, expressed as a percentage of the peak force, may be reduced either by decreasing the absolute load in a particular work situation, or by changing the situation in such a manner as to increase the mechanical efficiency of the body. For example, suppose that a force of 50 pounds is required to operate a control and that this represents all the force which an operator can apply to a control in this situation. In such a case, the operator could maintain this output for only a few seconds. If the operator must be extended beyond this limit it could be done in either of two ways: 1) by decreasing the required control force, or 2) by relocating the control--or otherwise changing the work situation --so that the body can produce more usable force. In the latter case the load would represent a smaller proportion of the operator's peak force, the relative load would be reduced, and the durability of the response should be increased.

One would infer from these considerations that when a subject is given the task of maintaining a constant output the endurance of his response should be greatest under those conditions which permit the development of the greatest momentary control force.

Since a substantial correlation was obtained between peak strength and the duration of a sub-maximal response one may use the principles derived from the peak force studies and apply them to work

situations quite different to those in which these data were obtained; that is, to those situations in which sub-maximal forces must be maintained for long periods of time. Also, since the measures of peak force are more reliable and more easily obtained than measures of duration, these results encourage the continuation of assessing the effects of anatomical variables on working efficiency by measuring peak strength.

IV. SUMMARY AND CONCLUSIONS

The purpose of this study was to determine the relationship between measures of maximum force of horizontal pull by the hand and the duration of a sub-maximal holding response at a variety of body positions. Five elbow-angles (95°, 110°, 125°, 140°, and 155°) were combined factorially with 2 thigh-angles (0° and 20°), and 2 knee-angles (110° and 150°) to produce 20 different body positions. At each position each of 10 subjects was measured to determine his peak force, and the time he could maintain a given force on a dynamometer handle. The magnitude of output to be maintained by each subject at all positions was his peak-output at the least efficient body positions; that is, with the elbow at 95°, the thigh at 0°, and the knee at 110°. Thus, the goal for each subject was dependent upon the force he could apply to the handle at the reference position.

A substantial correlation (.88) was obtained between peak force and the duration of the holding response. Thus, it may be assumed that a change in body position which increases peak output will reduce the effort required for maintaining a given force on the handle, and the duration of holding response will be increased. The main results of the investigation are as follows:

1. There was a small but statistically significant increase in peak strength and duration of the holding response as the thigh elevation was increased from 0° to 20°.

2. Both peak force and duration increased as the legs were straightened, but, again, this influence was fairly small.

3. The effect of the thigh position on these measures was dependent upon the knee-angle. The thigh position decreased in importance as the knee-angle was increased.

4. As the arm was straightened there was an increase in the strength and duration of the holding response.

5. Within the limits employed in this study, it may be stated that whether a person is required to apply a large force to a control for a short period of time, or whether a lesser force must be maintained over longer periods, performance will be best when the leg and arm are almost straight and the thigh is elevated above the horizontal.

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